III-V based magnetic semiconductors

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Progress in advanced material growth techniques such as molecular beam epitaxy has made it possible to grow a variety of new materials with novel properties for novel device applications. The magnetic properties of transition metals in semiconductors, for example, are of growing interest for the development of magnetoelectronic devices. As this new research field has emerged, a variety of new materials and artificial structures has been the subject of intensive study. Among them, diluted magnetic III-V semiconductors are expected to combine the properties of both magnetic materials and of semiconductors.

Recently, diluted magnetic semiconductors (DMS) - also known as semimagnetic semiconductors - have attracted the attention of the scientific and industrial community. DMS are semiconductors with a fraction of their constituent ions replaced by transition metal ions. In the absence of an external magnetic field, these materials behave in a similar manner to non-magnetic semiconductors.

Changing the concentration of the added magnetic ions can change the band gap and lattice parameters. Band-gap engineering in these materials can be applied to make them useful for various device applications. Until recently, practically all research on DMS involved II-VI based materials such as CdTe and ZnS because some magnetic ions, particularly Mn^{2+}, can be easily incorporated in II-VI compounds by substituting group II cations.

Although this made them relatively easy to prepare, difficulty in p- and n-doping of II-VI based DMS made this material system less attractive for applications. However, by using non-equilibrium growth conditions of low-temperature MBE a III-V based DMS, namely (In,Mn)As, was successfully grown by H. Munekata et al [1] in 1989.

Stimulated by the successful epitaxial growth of (In,Mn)As [1] and (Ga,Mn)As [2] by low-temperature MBE, the study of III-V based DMS has attracted much attention. The interplay between the three-dimensional quantisation and the magnetism associated with the introduction of for example Mn is certainly an interesting subject to follow. In addition, the feasibility of growing III-V based magnetic semiconductor heterostructures will offer unique opportunities for studying the spin-related phenomena in well controlled III-V systems.

M.Tanaka [3] reported two approaches to fabricate magnetic-semiconductor hybrid structures by epitaxial growth, namely epitaxial ferromagnet semiconductor heterostructures and DMS alloys and their heterostructures grown on semiconductor substrates. These two approaches are shown in Figure 1.

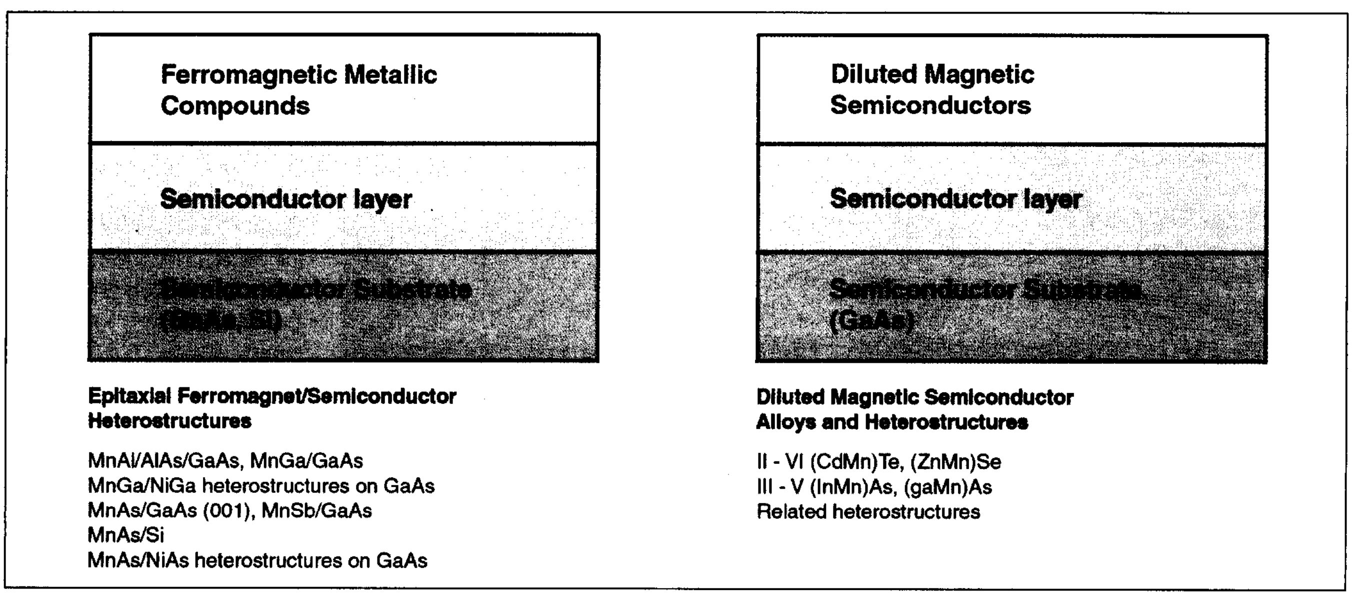

Figure 1: Schematic illustrations of two approaches for the integration of magnetic materials with semiconductors [3].

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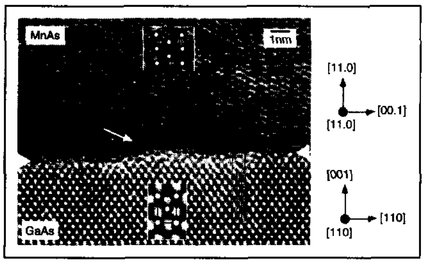

Figure 4: Cross-sectional HRTEM of the MnAs/GaAs structure demonstrating atomically abrupt interface. The inset shows models of the underlying crystal lattices. Courtesy of A. Trampert (Paul Drude Institute, Germany).

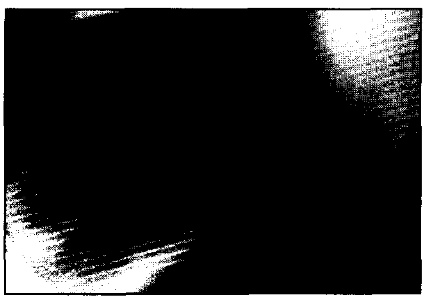

Figure 5: Cross-sectional TEM of a 50Å GaMnAs/ 30Å AlAs superlattice. Courtesy of M. Tanaka (University of Tokyo, Japan).

ferromagnets is to prepare epitaxial ferromagnetic thin films on semiconductor substrates. It is expected that ferromagnet/semiconductor heterostructures can lead to new device applications such as non-volatile memory and magnetic field sensors coupled with semiconductor circuitry.

Several groups have successfully grown by MBE single heterostructures, such as MnGa/GaAs (001), MnAs/GaAs (001), and MnAs/Si (001). However, epitaxial growth of ferromagnet/semiconductor multilayer structures is far more difficult. M. Tanaka [8] (University of Tokyo, Japan) recently reported on the MBE growth and properties of MnAs/GaAs/MnAs tril-ayer heterostructure on GaAs (111)B. Figure 6 shows the RHEED patterns during the growth of MnAs(10nm)/ GaAs(10nm)/MnAs(10nm) tri-layer heterostructure with electron-beam azimuth along the <110> of the GaAs substrate. Figure 6(a) is a (2x2)-(111)B GaAs surface of a 60 nm thick GaAs buffer layer prior to the growth of the bottom MnAs at 380°C. In Figure 6(b) is shown (3x2)-(0001) MnAs surface of a 10 nm thick bottom MnAs layer grown at 220°C. Figures 6(c) and (d) illustrate, respectively, the (111)B GaAs surface of a 10 nm thick GaAs spacer at a growth temperature of 220°C, and (2x2)-(0001) MnAs surface of a 10 nm thick top MnAs layer grown at 350°C.

The study of self-organised quantum dots (QDs) has attracted great interest both for fundamental physics and device applications. The self-organisation growth mechanism has also led to the formation of quantum dashes (QDHs). Due to the significant effect of the substrate orientation on epitaxial growth, S.P. Guo et al [9] (Tohoku University, Japan) studied InAs and (In,Mn)As nanostructures grown on GaAs (100), (211)B and (311)B substrates, as well as the effects of Mn as a surfactant on InAs nanostructures. InAs QDs with single size distribution were formed on GaAs (100) and (311)B, with InAs coverage of two monolayers (MLs) and four MLs, respectively. QDs with bimodal size distribution were observed on GaAs (211)B with an InAs coverage of six MLs. When they used a higher growth temperature for the (211) substrate, QDHs were formed. The (In,Mn)As QDs grown on GaAs (211)B showed improved size uniformity compared to those grown on (100) and (311)B GaAs substrates. InAs quantum wires (QWRs) were obtained when a layer of Mn was added on the growth front as a surfactant. Figure 7 shows the size distribution of (In,Mn)As grown at 350°C.

Ferromagnetic MnSb compound also grows epitaxially on GaAs substrate. It was found that the substrate reconstruction and the starting surface stoichiometry control the epitaxial orientation and in-plane magnetic anisotropy of MnSb. Mn_2Sb is a ferromagnetic metal with a tetragonal Cu_2Sb crystal structure. Mn_2As has the same crystal structure but with slightly smaller lattice constant and shows antiferromagnetic order. The Mn_2Sb/Mn_2As system shows an exchange inversion transition

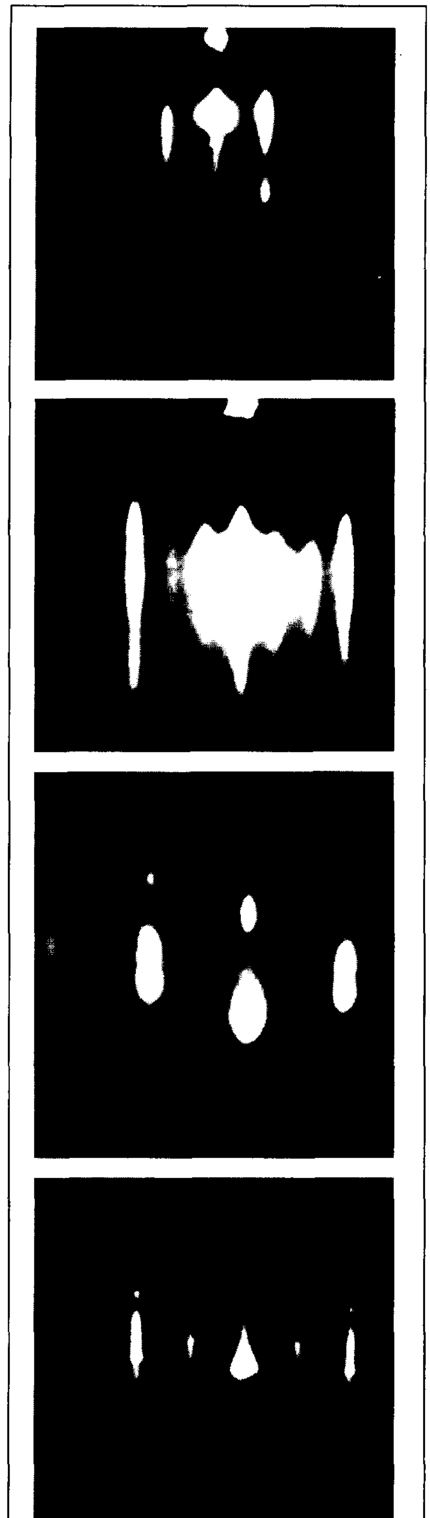

Figure 6: RHEED patterns during the growth of MnAs(10nm)/GaAs(10nm)/MnAs(10nm) trilayer heterostructure. Courtesy of M. Tanaka (University of Tokyo, Japan).

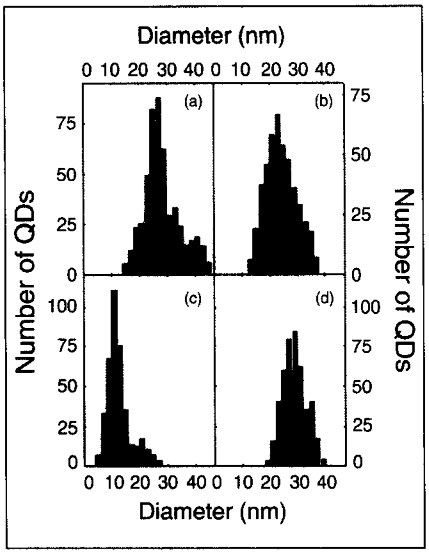

Figure 7: Size distribution of (In,Mn)As QDs grown at 350°C with (a) eight MLs of (In,Mn)As grown on GaAs (100), (b) five MLs of (In,Mn)As grown on GaAs (311)B, (c) six MLs and (d) nine MLs of (In,Mn)As grown on GaAs (211)B. Courtesy of H. Ohno (Tohuku University, Japan).

from ferromagnetic to antiferromagnetic order caused by the change of the Mn-Mn interactomic distance. It expected that this system has the possibility of controlling the magnetic structure of the $Mn_2Sb_{1-x}As_x$ thin films by changing lattice parameters. This can be achieved by substituting As for Sb.

Miyanishi et al [10] studied the MBE growth of $Mn_2Sb_{1-x}As_x$ films (x=0~0.21) on GaAs (001) and measured the compositional dependence of their lattice parameter and magnetic properties. From RHEED patterns it was found that these films have four-fold symmetry and that [100] $Mn_2Sb_{1-x}As_x$ is parallel to the [110] GaAs direction. X-ray analysis revealed that the growth direction is the c-axis normal to the surface. The magnetisation of $Mn_2Sb_{1-x}As_x$ layers was measured as a function of temperature for different As contents using a superconducting quantum interference device magnetometer. It was found that magnetisation decreases with increasing As content in the whole range of temperature.

Conventional electronic devices use only the charge of conduction electrons. However, there is a strong interest in devices whose operation depends on the electronic spin. Spin-polarised electrons, which occur naturally in ferromagnetic materials, can be injected from a ferromagnet into non-ferromagnetic materials.

A unique and important feature of DMS is the spin-spin exchange interaction between the localised magnetic moments of the magnetic ions and the conduction band electrons. This interaction affects the energy band, electronic structure and impurity level parameters of the semiconductors. This will result in new physical effects in the presence of strong magnetic fields.

Several spin-based semiconductor device schemes have been proposed and their practical realisation is being considered in many experiments worldwide. This new field of research (now called "Spin-Polarised Transport" or "Spin Electronics") is growing dramatically. Figure 8 illustrates a scheme, which applies the spin-injection to a semiconductor structure, yielding a spin-polarised field effect transistor (FET) [11]. The current-carrying medium is a high-mobility two-dimensional electron gas formed at the heterojunction between InAlAs and InGaAs. The spin-polarised carriers are injected and collected by ferromagnetic metal pads. A gate electrode is used to control the alignment of the carriers' spin with respect to the magnetisation vector in the second pad. As far as I know this device has not yet been demonstrated, but it is well within the reach of existing technologies.

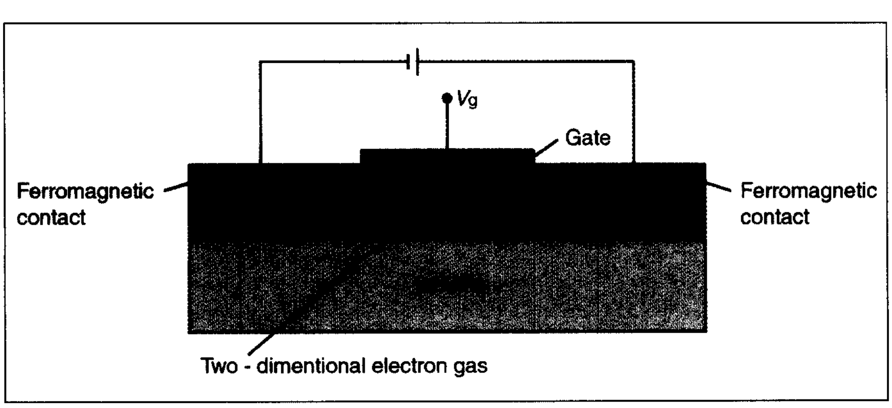

Figure 8: Schematic of a spin-polarised FET. V_g is the voltage applied to the gate [12].

Conclusion

It is believed that one of the most attractive new directions both for materials science and device applications will be magnetic-semiconductors which have properties of both magnetic materials and semiconductors. High-density non-volatile magnetic memory integrated with semiconductor ICs, magnetic sensors coupled with semiconductor circuits, and optical isolators integrated with semiconductor lasers for optical communication systems are predicted to be among potential applications [3].

Currently, a number of groups are working on MBE growth of III-V based DMS to advance understanding of this new material system and heterostructures based on it. Effort to expand the choice of magnetic elements to other transition metals is also in progress.

The field of spin-electronics is still in its infancy. However, the expected new effects will be the basis for electronic devices in this new and exciting field.

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